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Characterization of Porous Jet Density

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The density of porous granular jets is a difficult to measure characteristic of a class of non-metallic shaped charges. Flash x-ray experiments provide for a fairly accurate assessment of the diameter of the porous jet as a function of time and distance while the density measurement is more qualitative than quantitative. We utilize a new diagnostic that provides for a time resolved experimental technique of measuring the impulse applied by the porous jet during impact with a target. The impulse measurement allows for a quantitative assessment of the density of the porous granular jet as a function of time and distance. The new diagnostic technique provides the force-time history of the jet impacting a high strength bar. The force-time history is directly proportional to the product of the jet density and cross-sectional area ($\rho_j * A_j$) of the impacting jet. Computational analysis of the shaped charge liner collapse and jet formation provides the variable virtual origin characteristics which are used to define the X-T diagram for the jet. The virtual origin, initial liner density, and multiple data sets of the jet force-time history vs standoff allow us to characterize the density of the granular porous jet as a function of time and distance as well as jet velocity.

INTRODUCTION

We have recently developed a new diagnostic that provides for a time resolved experimental technique of measuring the impulse applied by a jet during impact with a target [1]. This approach allows for an accurate assessment of the density of a porous jet as a function of time and distance; a previously immeasurable characteristic of granular jets. The formation and penetration of porous granular jets from shaped charges is an area of continued interest and research to the ballistics community [2, 3]. The principal user of porous jets has historically been the oilwell industry to create holes in hydrocarbon-bearing geologic formations [4-9]. Porous jets are also used for military and civilian applications ranging from demolitions [10, 11] and the defeat of reactive armor [12, 13] to avalanche control [14].

The focus of this paper addresses a fundamental aspect of the nature of porous granular jets; characterization of the density of the jet as a function of time and distance. Analytical theory and computational science provide a fairly accurate

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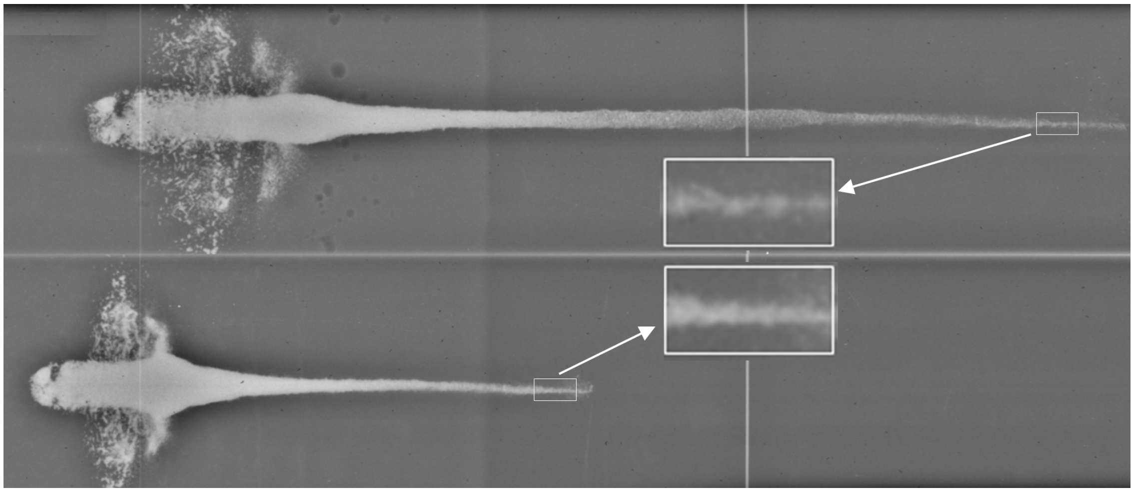


Figure 1. X-ray of porous jet showing change in jet density with time and distance.

assessment of the mass and velocity distribution of porous granular jets as a function of time and distance [15-18]. Images from flash x-ray experiments, like those shown in Figure 1, provide the diameter of the jet as a function of time and distance with fairly high accuracy. Unfortunately, density and velocity estimates of the porous granular jet from the experimental data do not instill a similar confidence. It is difficult to track a sub-50 micron particle with flash x-ray in order to estimate velocity as done with typical metallic jets. As a result, an accurate evaluation (experimental or simulated) of the density of a porous jet is elusive.

DIAGNOSTIC TECHNIQUE

The new diagnostic technique provides additional information about the porous jet density as a function of time and distance through the measurement of the force-time history of the jet impacting a high strength steel bar [1]. The technique is based on the classic Hopkinson-type strain bar, coupled with an interferometric velocimetry in lieu of strain gauges (prior method) as shown in Figure 2. The accuracy/uncertainty of the PDV system, after processing, is estimated to be 1% in velocity and time resolution.

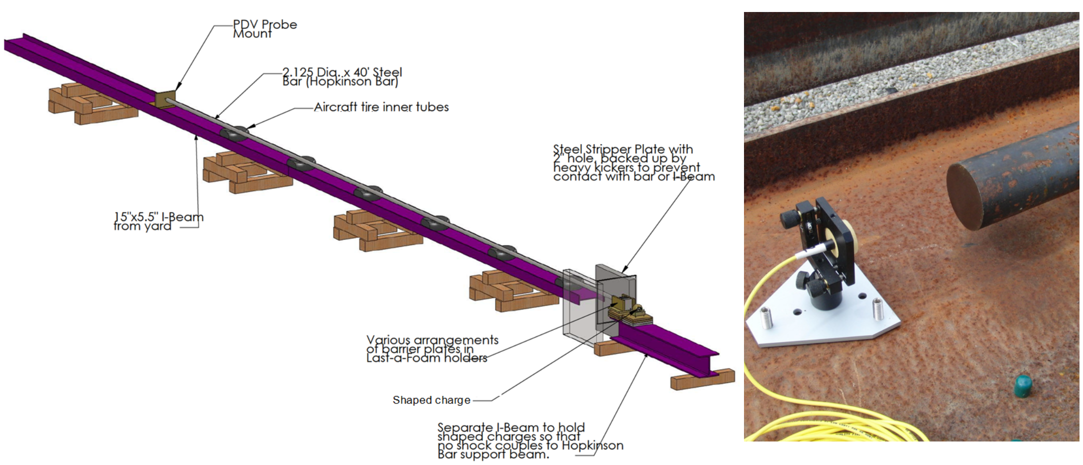


Figure 2. PDV-bar set-up and PDV probe lens at the end of the 40 foot long bar

The jet density characterization approach involves firing the porous jet into a steel PDV bar at multiple standoff distances (SOs). The particle velocity measured by the PDV at the opposite end of the bar from the jet impact is directly proportional to the jet density times jet cross-sectional area ($\rho_{j*}A_j$) of the impacting jet. Computational analysis of the shaped charge liner collapse and jet formation provides the virtual origin (or variable virtual origin) characteristics which are used to define the X-T diagram for the jet. The flash x-ray and computations provide the jet area as a function of time and distance. The virtual origin characteristics, jet area, and multiple impulse vs standoff data sets allow for the evaluation the density of the granular porous jet as a function of time and distance as well as jet velocity.

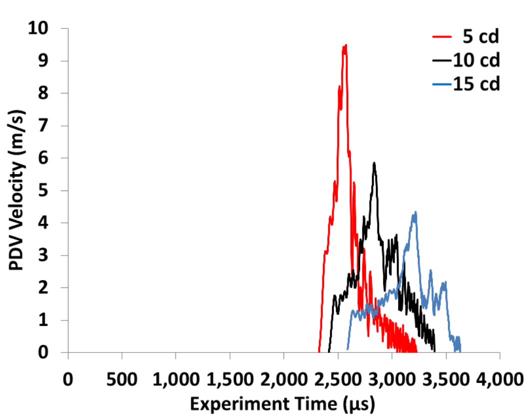
EXPERIMENTAL DATA

Plots of PDV velocity (m/s) vs experiment time (µs) at three SOs are shown in the left frame of Figure 3. These give the measured PDV velocity after propagation of the stress wave to the other end of the bar. The curves on the right of the figure are of the PDV velocity vs time referenced to the initiation time of the shaped charge.

Note that the accuracy of the PDV measured velocity-time wave form decreases with increasing plastic deformation of the bar. Plastic deformations to the impacted end of the bar due to the jet impact may complicate the interpretation of the measured PDV-bar signal in terms of time history. The experiment PDV values are compared to hydrocode simulations in Figure 4 using low and high strength steel bars showing the effect of the plastic deformation on the wave form. The most notable effects of the plastic deformation are damping of the higher frequency features and a slight change in the peak value followed by a larger change after the peak with the low strength steel. The primary area of interest in this study is before the value is reached peak.

JET VELOCITY ANALYSIS

Computational studies of the early time shaped charge liner collapse and jet formation are used to define the virtual origin (VO) characteristics of the jet. A "variable virtual origin" approach is used for tracking the kinematics of the jet. Plots of the VO-Z (position), VO-T (time), VO-A (jet area , A_j) from the computations and x-ray (Figure 1) are plotted in Figure 5 as a function of the jet velocity (cm/µs).



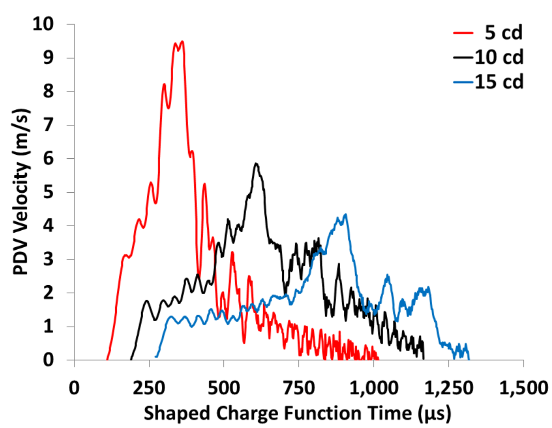


Figure 3. PDV velocity shown in experiment time (left) and referenced to the initiation time (right).

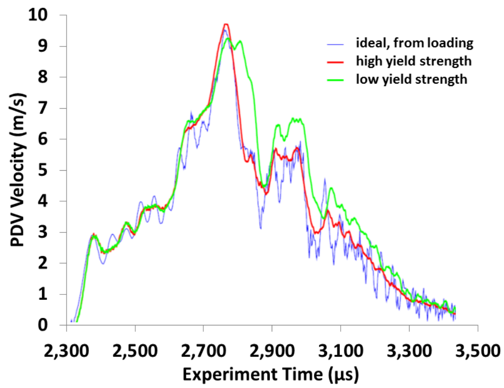


Figure 4. Effect of plastic deformation

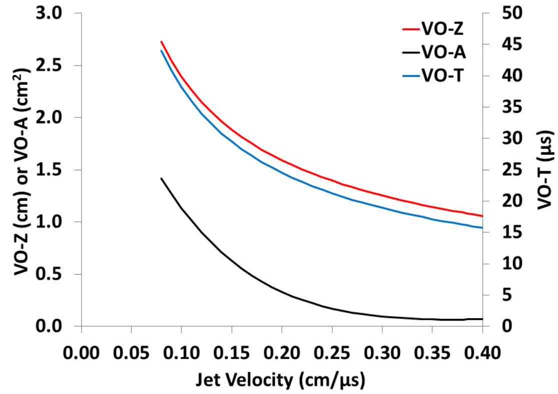


Figure 5. Virtual origin characteristics of jet.

The virtual origin characteristics of the jet and an X-T diagram are used to convert from a time based analysis of the jet characteristics to a jet velocity based analysis as shown in Figure 6. Using this approach, the three sets of PDV data at 5, 10, and 15 CDs standoff plotted versus time in the right frame of Figure 3 are now plotted versus jet velocity in Figure 7. This is a useful way to analyze the data because the virtual origin characteristics of the jet have been specified as a function of jet velocity and it is easier to compare the jet properties at the three SOs as a function of jet velocity.

The PDV velocity measured at the three SOs are proportional to the applied load from the jet impact with the bar. As such, the time integral of the PDV velocity is proportional to the total impulse applied by the jet to the bar. Time integrated PDV curves for the three SO data sets are shown in Figure 8. These plots shown the variation in total impulse delivered by the jet to the bar is less than 10% over the 5 to 15 CD standoff distances used in these tests.

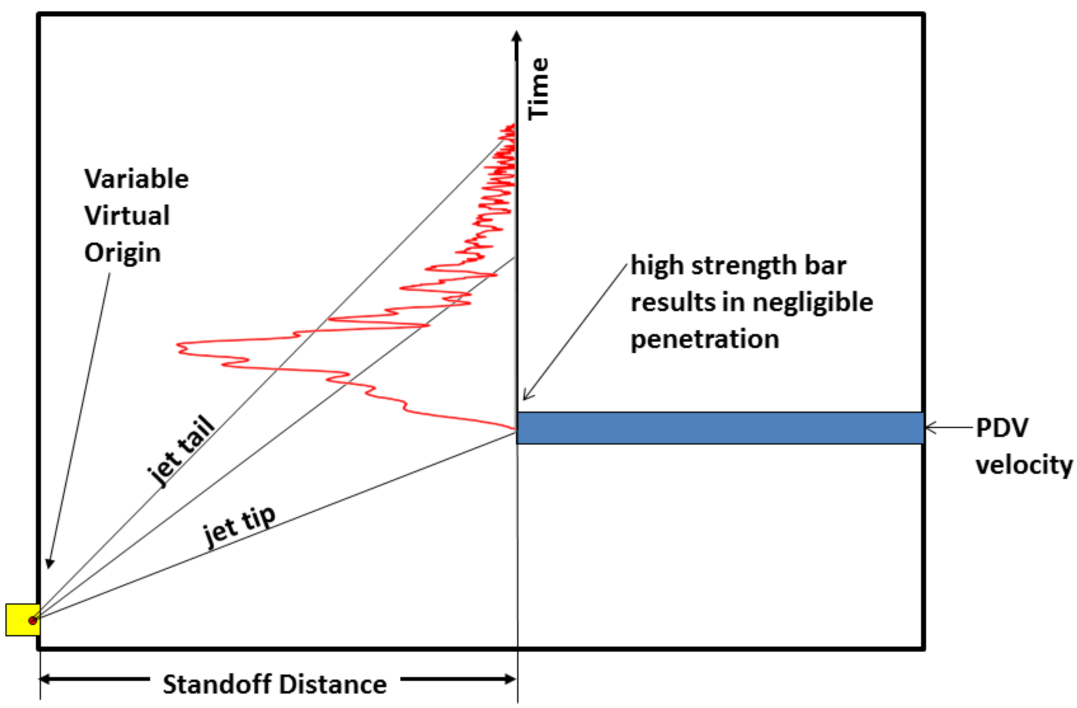


Figure 6. X-T diagram of the jet is used to convert from time basis to jet velocity basis.

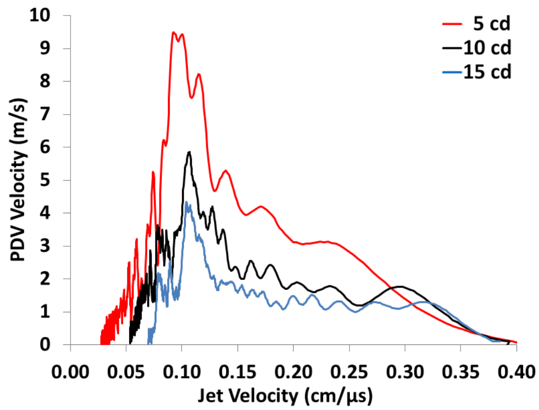


Figure 7. PDV velocity vs jet velocity

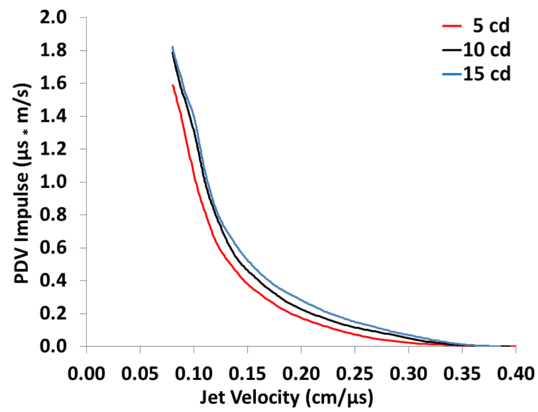


Figure 8. Jet impulse delivered to the bar

BAR STRESS ANALYSIS

The stress in the bar as a function of the PDV velocity is given in Eq. 1 [1]. The stress in the bar due to the applied load from the impacting jet is given in Eq. 2. By equating the applied jet force to the measured force, the jet density times jet cross-sectional area is proportional to the PDV velocity divided by the jet velocity squared. This $\rho_{j*}A_j$ relationship, as a function of the bar longitudinal sound speed, bar density and cross-sectional area, PDV velocity, and jet velocity squared, is given in Eq. 3.

$$F_b(t) = c_l \cdot \rho_b \cdot A_b \cdot v_{pdv}(t)/2 \tag{1}$$

$$F_j(t) = \rho_j \cdot A_j \cdot v_j^{\ 2}(t)/2 \tag{2}$$

$$\rho_j \cdot A_j = c_l \cdot \rho_b \cdot A_b \cdot v_{pdv}(t)/v_j^{\ 2}(t) \tag{3}$$

The raw PDV velocity curve data shown in Figure 7 was fit to an equation for smoothing in the subsequent analysis. Plots of the fitted PDV velocity vs jet velocity data is shown in Figure 9. Applying Eq. 3 to the fitted PDV velocity data in Figure 9, we are able to calculate the jet area times jet density as a function of the jet velocity for the 3 standoff experiments (Figure 10). The jet density times area (g/cm) has about the same magnitude as the PDV velocity (m/s) because of the bar size and properties.

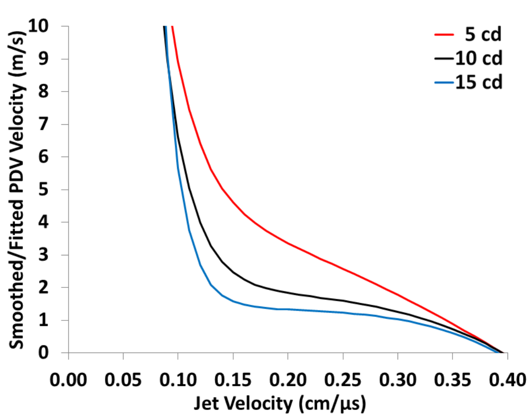


Figure 9. Fitted PDV velocity vs jet velocity

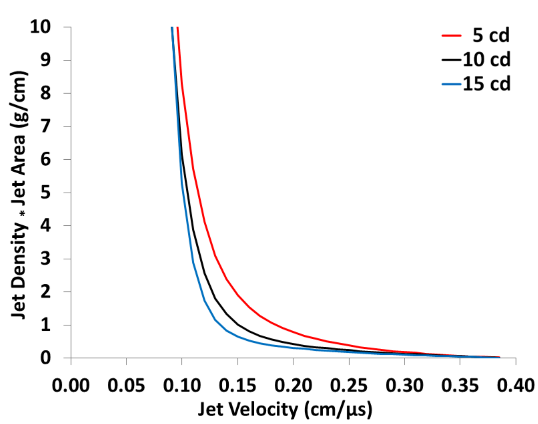


Figure 10. Jet density times jet area

JET DENSITY ANALYSIS

The jet density analysis utilizes the jet area that is derived from the flash x-ray data (Figure 1) and the jet cross-sectional area from the virtual origin (Figure 5). Additionally, the analysis presented here is based on the assumption that the area (or diameter) of the porous granular jet does change after the jet is initially formed. As such, the virtual-origin jet area (VO-A) plot in Figure 5 does not change with time or standoff. Thus, for a given jet velocity, the jet area remains constant. A comparison of the two x-ray images in Figure 1 indicate that this assumption of constant jet area for a given jet velocity is a mostly valid. The two small boxes in the figure are for the same velocity section of the jet at the two x-ray times.

By dividing the jet density times jet area vs jet velocity data shown in Figure 10 by the jet area vs jet velocity data of Figure 5, the three plots of jet density vs jet velocity shown in Figure 11 are created. Note that these plots are actually the relative density; the experimentally derived porous jet density divided by the original liner density. Additionally, note that the curves in Figure 11 are of the relative jet density at the time (and velocity) of the jet impacts with the bar.

Using the data of Figure 11 and of the virtual origin characteristics of the jet (Figure 5), we are able to plot the relative jet density vs jet length as shown in Figure 12. These three plots show the relative density of the jet vs jet position along the length of the jet at time of initial jet impact with the bar for the three SOs. These plots are consistent with the x-ray data which shows the lowest jet density at the tip with increasing density moving from the tip to the tail of the jet. A non-constant jet area model (i.e. increasing or decreasing jet diameter) can also be considered.

DIAGNOSTIC IMPROVEMENTS

There are a few diagnostic improvements for the PDV-bar technique that we plan to implement in future tests. These include the use of a very high strength material for the bar in order to reduce plastic deformation and the use of as small of a diameter bar as possible to maximize the PDV velocity and minimize bar ringing.

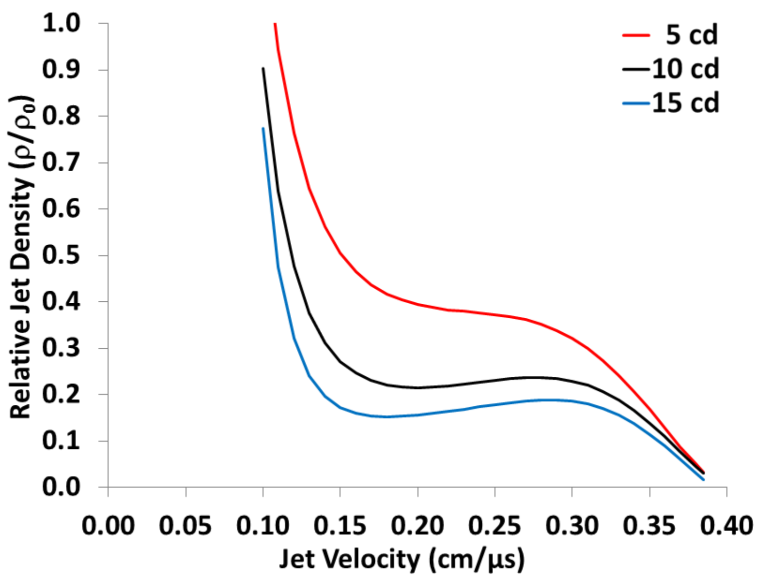


Figure 11. Relative jet density vs jet velocity at the time of impact with the bar

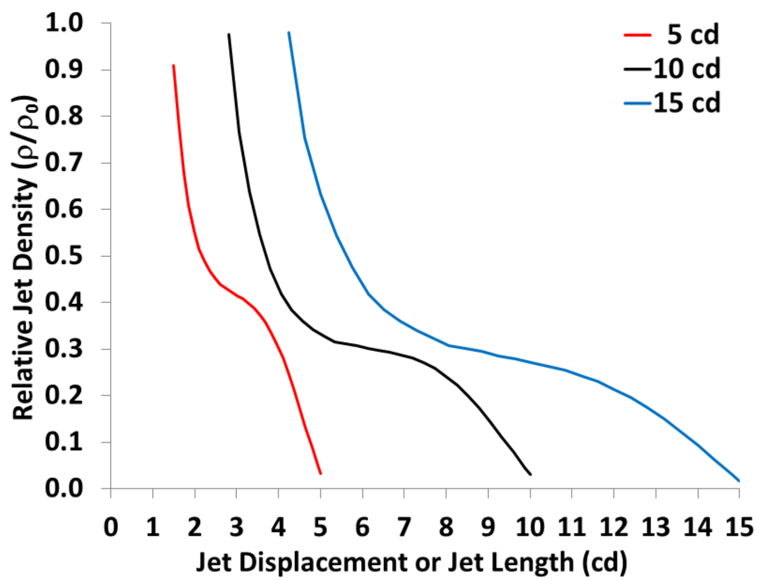


Figure 12. Relative jet density vs jet length (cd) at the initial bar impact time

CONCLUSIONS

Material density is a characteristic of porous granular jets that is difficult to measure. Flash x-ray experiments provide for a fairly accurate assessment of the diameter of the porous jet as a function of time and distance while the density assessment is more qualitative than quantitative. The new optical diagnostic technique (without electromagnetic interference), combined with computational modeling and flash x-ray experiments, provides for a time resolved experimental method of measuring the force-time history applied by the porous jet during impact with a target. The force-time history is directly proportional to the jet density, jet velocity, and jet cross-sectional area at impact. Knowledge of the jet velocity and area (measurable quantities) are then used to isolate the porous jet density.

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